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Optimal Cooperative MAC Protocol with Efficient Selection of Relay Terminals

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***Abstract*—A new cooperative protocol is proposed in the context of wireless mesh networks. The protocol implements on-demand cooperation, i.e. cooperation between a source terminal and a destination terminal is activated only when needed. In that case, only the best relay among a set of available terminals is re-transmitting the source message to the destination terminal. This typical approach is improved using three additional features. First, a splitting algorithm is implemented to select the best relay. This ensures a fast selection process. Moreover, the duration of the selection process is now completely characterized. Second, only terminals that improve the outage probability of the direct link are allowed to participate to the relay selection. By this means, inefficient cooperation is now avoided. Finally, the destination terminal discards the source message when it fails to decode it. This saves processing time since the destination terminal does not need to combine the replicas of the source message: the one from the source terminal and the one from the best relay. We prove that the proposed protocol achieves an optimal performance in terms of Diversity-Multiplexing Trade-off (DMT).**

I. Introduction

One of the major properties of Wireless Mesh Networks (WMNs) consists in the possibility of breaking long distances into a series of shorter hops. Apart from increasing the signal quality of the links, the mesh architecture allows the cooperative forwarding of data packet through intermediate terminals in the network. The forwarding scheme can be envisioned at several network layers. However, implementing the forwarding scheme at the lowest layers renders the protocol more reactive to network conditions and minimizes the transmission delay since each layer adds its own processing time and hence includes its own latency. Cooperative protocols implement two main functions: cooperative transmissions are managed at the physical (PHY) layer whereas the set up of the cooperation is done at the medium access control (MAC) layer. At the PHY layer, cooperative communications increase the wireless link reliability. In a cooperative scenario, a source terminal S sends data to a destination terminal D through a direct path. One or several relay terminals help the transmission by receiving the source message and forwarding it to D through a relaying path (see Figure 1). Hence the direct path is rendered more robust [1]–[4]. However, this comes at the price of bandwidth consumption so that the system operates at diminished capacity[1]. Hence, further optimization

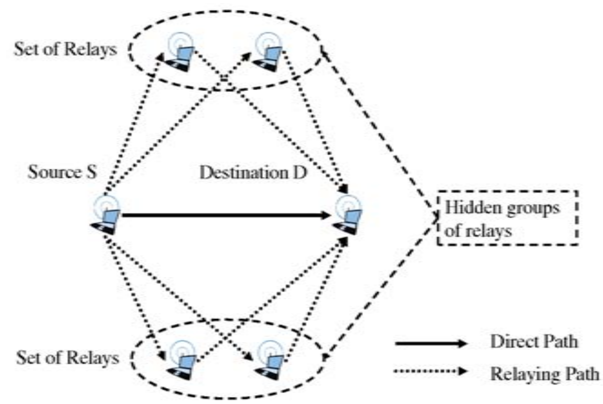

Fig. 1. Cooperation scenario with four relay terminals.

is required at the MAC layer in order to decrease the penalty in terms of bandwidth consumption. In particular, the selection of appropriate relay terminals is a main issue the design of cooperative MAC protocols.

One common way to compare cooperative transmission techniques is to compute the Diversity-Multiplexing Tradeoff (DMT) [5]. The DMT analysis of a transmission scheme yields the diversity gain $d(r)$ achievable for a spatial multiplexing gain r. The transmission scheme is said to have a diversity gain $d(r)$ and a spatial multiplexing gain r when the outage probability decays like $1/SNR^{d(r)}$ and the spectral efficiency scales like $r\log_2(SNR)$, where SNR denotes the received signal to noise ratio at the destination terminal. The diversity gain helps in quantifying the robustness of the S-D link and the multiplexing gain gives an hint on the capacity of the link. Both indicators should be maximized in order to get an optimal DMT curve. When $(m-1)$ relay candidates are involved in a cooperative scenario, the optimal DMT curve, $d(r) = m(1-r)$ for $0 \leq r \leq 1$, is achievable by protocols that implement both on-demand relaying and a selection of the best relay [6], [7]. In an on-demand relaying scenario [8], [9], the relay terminal is transmitting only when D fails in decoding the data transmitted by S. This approach allows maximization of the spatial multiplexing gain. Moreover, when cooperation is needed, only the best relay terminal retransmits the source message [10]. This allows maximization of the diversity order. Hence, the optimal DMT curve is achieved.

Two limitations arise when implementing cooperative pro-

[1]We use bandwidth as a general term for resource in a communication network. Bandwidth can be expressed in time slots, frequency bands, spreading codes or space time codes.

tocols with the two features mentioned above. First, one relay may be chosen even if it cannot improve the direct path. Second, the selection of the best relay is not collision free so that it is not possible to predict the amount of time required to carry out this task. The first and the second issues have been addressed in [11] and in [12], [13] respectively. However, the proposed protocols have not been designed with the purpose of optimizing both the DMT of the transmission scheme and the signaling needed to select the relays.

To tackle these issues, we improve the cooperative MAC (Medium Access Control) protocols in [6], [7] with the following additional features:

- *splitting algorithm for fast relay selection*: a splitting algorithm can find the best relay terminal, on average, within at most 2.507 slots even for an infinite number of relay candidates [14], [15]. Collision between relay candidates are not avoided but the contention time is completely characterized. Splitting algorithms have not been used in the design of DMT-optimal protocols yet.
- *pre-selection of the relay terminals*: the relevance of the cooperation scheme is guaranteed by pre-selecting only terminals that are able to improve the direct transmission. Inefficient cooperation is now avoided.
- *source message dropping*: the destination terminal discards the source message when it fails to decode it. This saves the processing time required to combine the source signal and the best relay signal, without sacrificing the optimality of the DMT.

We show that this on-demand relaying protocol with selection of the best relay terminal provides an optimal performance in terms of DMT. This cooperative protocol has been designed in the context of IEEE 802.11-based mesh networks. Though restricted to this standard in this paper, we believe that our proposal can also be applied to other wireless systems such as wireless sensor networks, broadband wireless networks, and broadcast wireless systems. In section II, the protocol is described in details. Section III presents the DMT analysis of the protocol. In particular, we show the optimality of the DMT when the relaying scheme is based on a fixed Amplify-and-Forward (AF) method. We conclude in section IV.

II. On-demand Relaying with Selection of the Best Relay Terminal

A. System model

We consider a slow Rayleigh fading channel model in which delay constraints are on the order of the channel coherence time. Each relay terminal cannot transmit and listen simultaneously (half duplex constraint). Moreover, transmissions are multiplexed in time, they use the same frequency band. The channel gain h_{ij} between a transmitting terminal i and a receiving terminal j, is assumed to be accurately measured by the receiver j, but not known to the transmitter i. We also assume that the channel gain h_{ij} is identical to the channel gain h_{ji}. This assumption is relevant since both channels are using the same frequency band. Statistically, channel gains h_{ij} are modeled as i.i.d circularly symmetric complex Gaussian random variables with zero mean and equal variance σ^2. Let P be the power transmitted by each terminal and σ_w^2 be the variance of the AWGN (Additive White Gaussian Noise) in the wireless channel. We define $SNR = P/\sigma_w^2$ to be the effective signal-to-noise ratio.

We also restrict our study to a single source-destination pair. Among terminals within the range of both the source terminal and the destination terminal, we focus on $(m-1)$ specific terminals. These terminals are available for implementing a cooperative transmission and they are not allocated to any other transmission. However, these $(m-1)$ terminals are likely to cause collision if they try to transmit data all at once. The knowledge of m at the participating terminals is not mandatory. This issue will be addressed in the next subsection. All other terminals are assumed to remain silent because they do not implement a cooperation functionality, or their cooperation functionality has been switched off. Hence, no extra interference occurs from neighboring terminals. In any case, if a terminal should interfere with the cooperative transmission, the proposed protocol is implementing classical error recovery mechanisms.

B. Protocol Description

1) Cooperation Mode Activation: the cooperation mode is activated at terminal R_i, $1 \leq i \leq (m-1)$, upon reception of a data frame from any source terminal S. This triggers the relay selection process at the relay candidates. The data frame is stored when R_i is implementing the cooperation functionality and R_i is not already involved in any other transmission. When terminal D succeeds in decoding the data frame, it sends an acknowledgment frame (ACK). Otherwise, terminal D discards the data frame and sends a signaling frame (CFC for Claim For Cooperation) [9]. This saves the processing time required to combine the source signal and the best relay signal, without sacrificing the optimality of the DMT. Note that the data frame from S contains an additional control field on the source address. Hence, when the checksum on the entire frame is wrong and the checksum on the source address is good, the destination terminal explicitly infers that the message from the source terminals is erroneous but the source ID is correct. So the destination terminal is able to send a CFC with the source address. When the CFC frame is lost, the protocol implements classical error recovery mechanisms[2]. When a terminal R_i stores the source message, it waits for either an ACK frame or a CFC frame. If any of these two frames is not received within a given time-slot, the source message is discarded at terminal R_i. Hence, only terminals that have received both the data frame and the CFC frame trigger the relay selection process[3]. Moreover, only terminals that improve the direct path are allowed to compete for best relay terminal. To decide whether a terminal R_i is pre-selected or not, a suitability metric u_i is

[2] Note that timeouts should be delayed to take into account possible cooperative transmissions.

[3] Terminals that just receive either an ACK frame or a CFC frame ignore the signaling frame.

used. This metric is also used to evaluate the relay candidates during the splitting algorithm. This metric can be the related to the channel gain h_{R_iD}. A more accurate approach consists in considering a suitability metric related to the capacity of the relayed path in (4). So the best terminal is the one that can achieve the best link capacity. A relay candidate is pre-selected if the capacity of the cooperative transmission through this relay is above a given threshold. This threshold can be the target data rate R.

2) Splitting algorithm: consider a time-slotted system with $(m-1)$ relay candidates. Each terminal R_i has a suitability metric u_i, defined as the mutual information of the cooperative transmission from S to D, through terminal R_i in (4). The goal is to select the terminal with the highest metric. The metrics are continuous and i.i.d. with complementary CDF (CCDF) denoted by $F_c(u) = \Pr[u_i > u]$. Therefore, the $F_c(.)$ is monotonically decreasing and invertible. The algorithm is specified using three variables $H_L(k)$, $H_M(k)$, and $H_{\min}(k)$ following [14]. $H_L(k)$ and $H_M(k)$ are the lower and upper metric thresholds, respectively, such that a terminal R_i transmits at time slot k if and only if its metric u_i satisfies $H_L(k) < u_i < H_M(k)$. $H_{\min}(k)$ tracks the largest value of the metric known up to slot k above which the best metric surely lies.

Initialization: in the first slot ($k = 1$), the parameters are initialized as follows:

- $H_L(1) = F_c^{-1}(1/N_r)$,
- $H_H(1) = \infty$,
- and $H_{\min}(1) = 0$.

The parameter N_r denotes the number of possible relays and should be set to $(m-1)$. So, each terminal should know the value of N_r. In the general case when this value is not known at each terminal, it can be overestimated by the number of terminals in the range of D. Terminal D generally knows this number through upper layer protocols.

Transmission rule: at the beginning of each slot, each terminal locally decides to transmit if and only if its metric lies between $H_L(k)$ and $H_H(k)$.

Feedback generation: at the end of each slot, the destination terminal broadcasts to all terminals a two-bit feedback: (i) 0 if the slot was idle (when no terminal transmitted), (ii) 1 if the outcome was a success (when exactly one terminal transmitted), or (iii) e if the outcome was a collision (when at least two terminals transmitted).

Response to feedback: let $split(a, b) = F_c^{-1}(\frac{F_c(a)+F_c(b)}{2})$ be the split function. Then, depending on the feedback, the following possibilities occur:

- if the feedback (of the kth slot) is an idle (0) and no collision has occurred so far, then set
  - $H_H(k+1) = H_L(k)$,
  - $H_L(k+1) = F_c^{-1}(\frac{k+1}{N_r})$,
  - and $H_{\min}(k+1) = 0$ (see Figure 2).
- if the feedback is a collision (e), then set
  - $H_L(k+1) = split(H_L(k), H_H(k))$,
  - $H_H(k+1) = H_H(k)$,
  - and $H_{\min}(k+1) = H_L(k)$ (see Figure 3).
- if the feedback is an idle (0) and a collision has occurred in the past, then set
  - $H_H(k+1) = H_L(k)$,
  - $H_L(k+1) = split(H_{\min}(k), H_L(k))$,
  - and $H_{\min}(k+1) = H_{\min}(k)$ (see Figure 4).

The channel coefficient $|h_{R_iD}|^2$ between terminal R_i and the destination terminal D serves as the suitability measure for the figures 2, 3, and 4. The parameter h_{R_iD} is a Rayleigh distributed variable such that the variable $|h_{R_iD}|^2$ is exponentially distributed. We assume that the random variable $|h_{R_iD}|^2$ has a variance unity. Again, link capacities can serve as suitability measures in practical implementations.

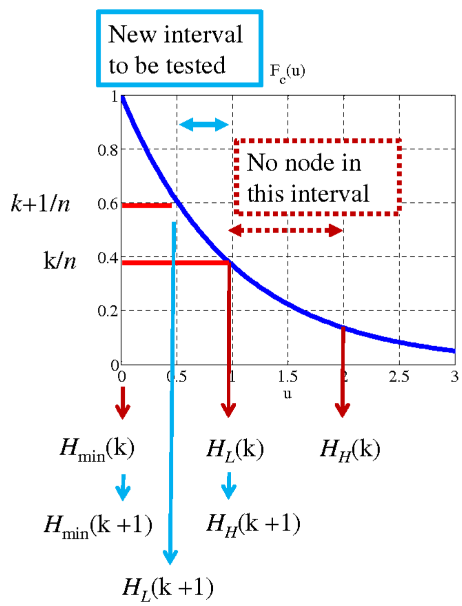

Fig. 2. Threshold adjustments of the splitting algorithm when the feedback is 0 (idle) and no collision has occurred so far.

Termination: The algorithm terminates when the outcome is a success (1).

3) Data transmission: when the destination terminal sends its last feedback, the best relay terminal sends a copy of the data frame using a fixed AF forwarding scheme. The destination receives the signal from the best relay terminal. When D succeeds in decoding the data frame, D sends an ACK frame (see Figure 5). Otherwise, D remains silent and the timeout at the source terminal triggers a re-transmission.

4) Protocol design in the context of IEEE 802.11-based networks: we give here some additional comments on the protocol design.

- RTS/CTS optional access method: several cooperative MAC protocols rely on the exchange of modified Request-to-Send (RTS) and Clear-to-Send (CTS) signaling frames [11]–[13]. If CTS frames transmitted by the destination terminal D can be modified, we can infer that channel state information is available at the transmitter. Hence, the source can actually choose not to transmit

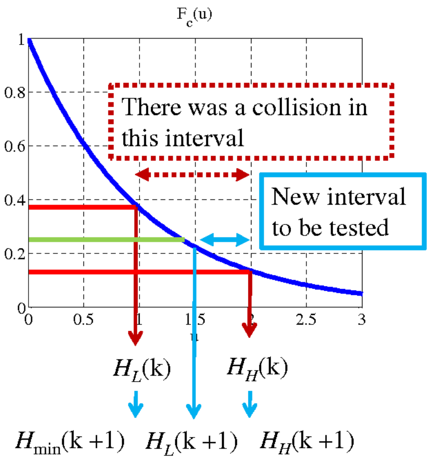

Fig. 3. Threshold adjustments of the splitting algorithm when the feedback is e (collision).

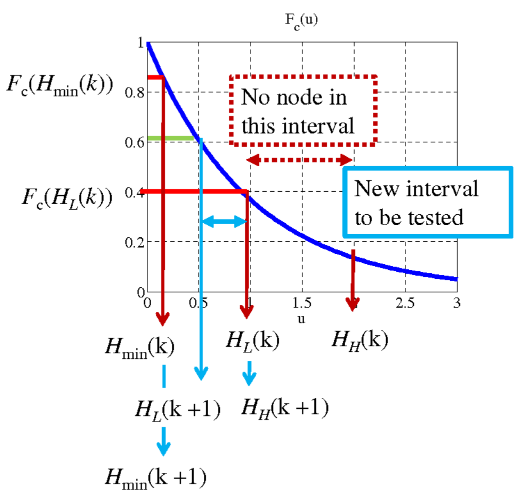

Fig. 4. Threshold adjustments of the splitting algorithm when the feedback is 0 (idle) and a collision has occurred in the past.

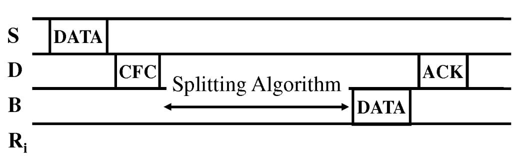

Fig. 5. Frame exchange sequence in the protocol using the basic IEEE 802.11 access method (S is the source terminal, D is the destination terminal, B is the best relay terminal, and R_i is a relay candidate).

when a target capacity cannot be supported. This gives rise to new cooperative protocols, the study of which is left for future work.

- NAV modification: the Network Allocation Vector (NAV) values at each terminal should be increased according to the new frame scheduling. This should avoid unnecessary soundings by neighboring terminals.
- Error recovery mechanism: as soon as a frame is missing, when a collision occurs, or when the set of efficient relays is empty, the source message is discarded at the relay terminals and the source terminal triggers a retransmission after a given timeout.

III. DMT Analysis of the On-Demand Cooperative Protocol

The DMT analysis focusses on the transmission part of the protocol, i.e. on the PHY layer. Indeed, the DMT has not been designed to take into account signaling overhead. So in the context of cooperative transmissions, the DMT analysis fails in taking into account the overhead due to relay selection. However, the fact that only appropriate terminals have been pre-selected for the best relay competition can be considered. Note also that existing DMT analyses of cooperative transmissions do not provide a higher level of accuracy. For instance, the relay selection is not taken into account in the DMT analysis of [2] and the overhead required to distribute space-time codes to relay terminals has not been taken into account in the DMT analysis in [8]. Further studies should provide a means to include MAC overhead in the capacity computing and then in DMT analyses. A first step toward this objective has been proposed in [16]. The complete study is currently in progress.

The protocol is denoted OAPD for On-demand fixed Amplify-and-forward relaying with relay Pre-selection and frame Dropping. We characterize our channel models using the system model described in the previous section, and a time-division notation; frequency-division counterparts to this model are straightforward. We use a base-band-equivalent, discrete-time channel model for the continuous-time channel. Three discrete time received signals are defined in the following. Here, $y_{ij}(n)$ denotes the signal received by terminal j and transmitted by terminal i. During a first time-slot, D and the best relay terminal B are receiving signals from S

$$y_{SD}(n) = h_{SD}x(n) + w_{SD}(n) \tag{1}$$

$$y_{SB}(n) = h_{SB}x(n) + w_{SB}(n) \tag{2}$$

for $n = 1, 2, ..., T_M/2$, where T_M denotes the duration of time-slots reserved for each message. When terminal D succeeds in decoding the data frame from S, no signal is transmitted by the best relay terminal B. Otherwise, B transmits a new signal using a fixed AF scheme, and D is receiving

$$y_{BD}(n) = h_{BD}[\beta y_{SB}(n)] + w_{BD}(n)$$

for $n = T_M/2+1, ..., T_M$. The noise $w_{ij}(n)$ between transmitting terminal i and receiving terminal j are all assumed to be i.i.d. circularly symmetric complex Gaussian with zero mean and variance σ_w^2. Symbols transmitted by the source terminal S are denoted $x(n)$. For simplicity, we impose the same power constraint at both the source and the relay: $E[|x(n)|^2] \leq P$ and $E[|\beta y_{SB}(n)|^2] \leq P$. We implement a fixed AF cooperation scheme. So the normalization factor β must satisfy

$$\beta^2 = \frac{P}{|h_{SB}|^2 P + \sigma_w^2}$$

We assume that the source and the relay each transmit orthogonally on half of the time-slots. We also consider that a perfect synchronization is provided at the block, carrier, and symbol level. We define the diversity order $d_{OAPD}(r)$ of the OAPD protocol by

$$d_{OAPD}(r) = \lim_{SNR\to\infty} -\frac{\log[p^{out}_{OAPD}(SNR, r)]}{\log(SNR)}$$

The probability $p^{out}_{OAPD}(SNR, r)$ is the outage probability for a signal to noise ratio SNR and a spatial multiplexing gain r define by

$$r = \lim_{SNR\to\infty} \frac{R}{\log_2(SNR)}$$

where R is the spectral efficiency of the transmission (in b/s/Hz). For high SNR values, we use

$$R = r\log_2 SNR$$

Assuming that $(m-1)$ terminals are available, the OAPD protocol is in outage if all the relay terminals fail in improving the direct transmission. So the outage probability $p^{out}_{OAPD}(SNR, r)$ of the OAPD protocol is

$$\begin{aligned} p^{out}_{OAPD}(SNR, r) &= \Pr[I_D \leq R] \\ &\times \Pr[\bigcup_{i=1}^{m-1} (I^{(i)}_{APD} \leq \frac{R}{2}) | I_D \leq R] \end{aligned}$$

where I_D is the mutual information of the direct transmission

$$I_D = \log_2(1 + SNR|h_{SD}|^2) \tag{3}$$

and $I^{(i)}_{APD}$ is the mutual information of the relayed transmission using fixed AF cooperation scheme at terminal R_i and implementing frame dropping at the destination terminal

$$I^{(i)}_{APD} = \frac{1}{2}\log_2[1 + f(SNR|h_{SR_i}|^2, SNR|h_{R_iD}|^2)] \tag{4}$$

where

$$f(x, y) = \frac{xy}{x + y + 1}$$

There is no $SNR|h_{SD}|^2$ term in $I^{(i)}_{APD}$ because the source message is now dropped at the destination terminal D when D fails in decoding the message from S. Since the event $I_D \leq R$ is independent of the events $I^{(i)}_{APD} \leq R/2$ for $1 \leq i \leq (m-1)$, we have that

$$p^{out}_{OADP}(SNR, r) = \Pr[I_D \leq R]\Pr[\bigcup_{i=1}^{m-1} (I^{(i)}_{APD} \leq \frac{R}{2})]$$

With (3), we have that

$$\Pr[I_D \leq R] = \Pr[|h_{SD}|^2 \leq SNR^{r-1}]$$

for high SNR values. The random variables h_{SR_i} and h_{R_iD} being mutually independent, for high SNR, we have that

$$p^{out}_{OADP}(SNR, r) \leq \Pr[|h_{SD}|^2 \leq SNR^{r-1}] \times \prod_{i=1}^{m-1} P_i \tag{5}$$

where the probability P_i is defined as

$$P_i = \Pr[f(SNR|h_{SR_i}|^2, SNR|h_{R_iD}|^2) \leq SNR^r]$$

for $1 \leq i \leq (m-1)$.

From Lemma 2 in [10], we have that

$$\lim_{SNR\to\infty} \frac{\log\{\Pr[|h_{SD}|^2 \leq SNR^{r-1}]\}}{\log(SNR)} = r - 1 \tag{6}$$

because $|h_{SD}|^2$ is an exponential random variable with parameter σ^2. For the other terms, we first adapt the result of Lemma 4 in [10]

$$\Pr[f(\rho a, \rho b) \leq \rho^r] \leq \Pr[\min(a, b) \leq \rho^{r-1} + \sqrt{\rho^{r-2}(\rho^r + 1)}]$$

Thus, we have that

$$\begin{aligned} P_i \leq & \Pr[\min(|h_{SR_i}|^2, |h_{R_iD}|^2) \leq SNR^{r-1} \\ & + \sqrt{SNR^{r-2}(SNR^r + 1)}] \end{aligned}$$

The random variable $\min(|h_{SR_i}|^2, |h_{R_iD}|^2)$ is an exponential variable with parameter $2\sigma^2$ because $|h_{SR_i}|^2$ and $|h_{R_iD}|^2$ are two i.i.d. exponential random variables with equal parameter σ^2. So, from Lemma 2 in [10] and the fact that $\sqrt{SNR^{r-2}(SNR^r + 1)} \to SNR^{r-1}$ as $SNR \to +\infty$, we have that

$$\lim_{SNR\to\infty} \frac{P_i}{\log(SNR)} = (r - 1) \tag{7}$$

for $1 \leq i \leq (m-1)$.

Using (6) and (7) in (5), we have that

$$\lim_{SNR\to\infty} -\frac{\log[p^{out}_{OAPD}(SNR, r)]}{\log(SNR)} = m(1 - r)$$

Hence, the diversity curve $d_{OAPD}(r)$, i.e. the DMT of the OAPD protocol, is

$$d_{OAPD}(r) = m(1 - r) \tag{8}$$

Hence, when $(m-1)$ relay terminals are involved, the OAPD protocol achieves the optimal DMT curve reaching the two extremes points $d^*(0) = m$ and $d^*(1) = 0$ (see Figure 6). Note that the only information provided by the DMT curve is that the data rate of the overall transmission scales like a direct transmission, even in presence of a cooperative relaying. In particular, the overheard induced by the additional signaling frames (CFC, splitting algorithm) does not appear in (8) because the DMT analysis is just providing a rough estimate of the achieved multiplexing gain.

IV. Conclusion

The purpose of the study is the design of a DMT optimal access protocol in the context of IEEE 802.11 mesh networks. The designed protocol has two basic features: on-demand cooperation and selection of the best relay terminal. Cooperation is activated on-demand, i.e. only when a destination terminal fails in decoding the message of a source terminal. This approach allows maximization of the spatial multiplexing gain, i.e the capacity of the source-destination link. Moreover, when cooperation is needed, only the best relay terminal retransmits

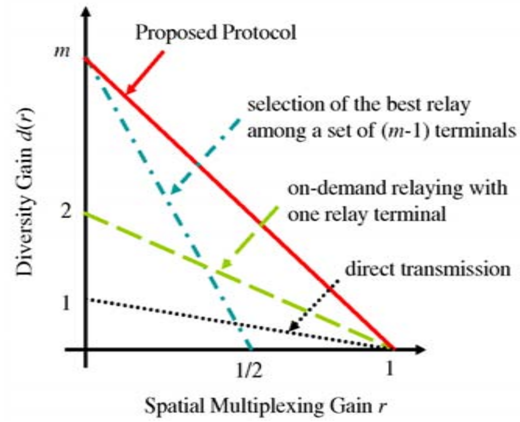

Fig. 6. DMT curves of four protocols: the proposed protocol, the direct transmission, the protocol implementing the selection of the best relay among a set of $(m-1)$ terminals in [10], and the on-demand relaying with one relay in [8].

the source message. This allows maximization of the diversity order, i.e the robustness of the link. Hence, an optimal DMT curve is achieved. We add three other features that guarantee both a fast and an efficient relay selection. Using a splitting algorithm, the time required to select a best relay terminal is now fully characterized. Moreover, only terminals that can improve the direct transmission are pre-selected. So inefficient cooperation is now avoided. Finally, the destination terminal discards the source message when it fails to decode it. This saves processing time without sacrificing the optimality of the DMT. When $(m-1)$ terminals are situated in the range of both a source terminal S and a destination terminal D, a diversity gain of m is provided while a spatial multiplexing gain of one is achieved. Thus, the protocol implements a DMT optimal transmission scheme. The study focusses on a fixed AF transmission scheme but it can also be applied to a selective decode-and-forward approach. Further studies should be able to take signaling overhead into account in DMT analyses. This work is currently in progress.

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